Design of PhotoFET for monolithic active pixel sensors in high energy physics and biomedical imaging applications

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Monolithic active pixel sensors using standard low-cost CMOS technology available from industrial manufacturers have demonstrated excellent tracking performances for minimum ionising particles in high energy physics and biomedical imaging applications. A new design of PhotoFET is presented. This structure offers the advantage of integrating amplification inside the sensing element using a PMOS transistor with a high sensitivity and a large output dynamic range. The proposed PhotoFET has been implemented with the AMS 0.35 µm process. The main results of measurements are presented.

Introduction: CMOS monolithic active pixel sensors are charged particle tracking devices, integrating on the same substrate the radiation sensitive detector element with its front-end readout electronics [1, 2]. They are fabricated using standard CMOS processes available through many commercial microelectronics foundries. The detection of charged particles with a CMOS sensor relies on a key element that is made using a twin-well technology with an *n*-well/*p*-substrate diode in order to achieve close to 100% detection efficiency. This diode collects, through thermal diffusion, the charge generated by the impinging particles in the thin, mostly undepleted, silicon layer underneath the readout electronics. The charge collected by each diode is directly converted to an electronic signal at the pixel level.

The front-end readout electronics for ionising particle detection in pixels is inspired by the sensors originally developed for visible light imaging in which a source follower based on NMOS transistors is used. This structure does not ensure a high sensitivity, nor optimal noise performance for the sensors owing to its low voltage gain. Moreover, this kind of sensor needs a reset before readout in order to maintain a large output dynamic range because of the leakage current of the diode, which discharges continuously the capacitor of the diode. In this Letter, an architecture using current mode signal processing is presented. This structure is called a PhotoFET. It offers the main advantage of integrating amplification inside the sensing element in order to obtain a high sensitivity to ionising particles and a large output dynamic range.

PhotoFET structure and operation: The proposed PhotoFET is shown in Fig. 1, in which a standard PMOS transistor M_1 is made in a floating *n*-well implanted in the *p*-type substrate. This provides a built-in signal amplification achieved by charge-to-current conversion. Since the charge-collecting diode D_1 is continuously reverse biased, as shown in Fig. 1, the collected charge affects the threshold voltage of M_1 through the *n*-well voltage potential and hence modulates the output drain current. The sensitivity is increased by applying the *n*-well voltage back to the gate of M_1 via the source follower transistor M_2. Also the PhotoFET intrinsically compensates for the leakage current of the collection diode D_1 by the diode D_2.

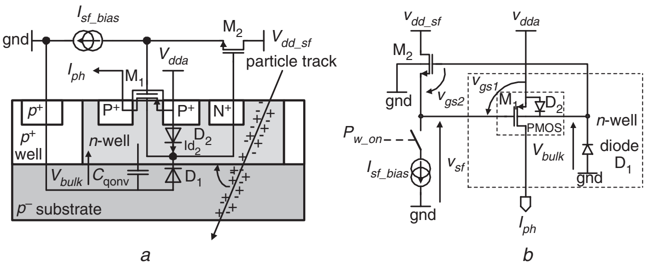

Fig. 1 *PhotoFET pixel structure and schematic diagram*

a Pixel structure
b Schematic diagram

The transistor M_2 determines the operation region of the PMOS transistor. The linear sensor response can be achieved by biasing the PMOS transistor in strong inversion. The DC characteristics between the drain current I_{ph} and its bulk voltage V_{BS1} can be written as follows:

$$I_{ph} = -\frac{\mu_p}{2}\frac{W_1}{L_1}C_{OX}(V_{GS1} - V_{T1})^2 \tag{1}$$

$$V_{T1} = V_{TO_p} - \gamma_p\left(\sqrt{\left|2\Phi_{F_p}\right| + V_{BS1}} - \sqrt{\left|2\Phi_{F_p}\right|}\right) \tag{2}$$

and

$$V_{GS1} = -V_{GS2} + V_{BS1} \tag{3}$$

where V_{T1} is the threshold voltage of M_1, V_{BS1} is the bulk-to-source voltage of M_1 and V_{GS2} is the gate-to-source voltage of M_2. Since the junction capacitance of the *n*-well/substrate diode is typically of a few femto farads, the voltage variation of V_{BS1} for 10–10^3 collected electrons does not exceed a few tens of millivolts. Thus (2) can be approximated to:

$$V_{T1} \simeq V_{TO_p} - \gamma_p\sqrt{\left|2\Phi_{F_p}\right|}\left(\frac{1}{2}\frac{V_{BS1}}{\left|2\Phi_{F_p}\right|}\right) \tag{4}$$

A quadratic DC-relation between the bulk-to-source voltage and the output current of the PMOS transistor is obtained by substituting (3) and (4) into (1):

$$I_{ph} = -\frac{\mu_p}{2}\frac{W_1}{L_1}C_{OX}(-V_{GS2} + aV_{BS1} - V_{TO_p})^2 \tag{5}$$

where $a = 1 + (\gamma_p/2\sqrt{|2\Phi_{F_p}|})$. The small-signal output current i_{ph} to the collected electrons via the bulk-to-source voltage variation v_{BS1} of M_1 can be calculated by:

$$i_{ph} = \left(g_{mb1} + \frac{g_{m2}}{g_{m2} + g_{mb2}}g_{m1}\right)v_{BS1} \tag{6}$$

where g_{m1} and g_{mb1} are the gate and bulk transconductances of M_1, respectively, and g_{m2} and g_{mb2} are the gate and bulk transconductances of M_2.

Normally, the integration of the PMOS transistor increases the size of the collection diode D_1. This modification of the diode size also increases the capacitance of the diode and so reduces the charge-to-voltage factor of the pixel. However, the PMOS integrated inside the *n*-well constitutes an amplification. This amplification compensates for the charge-to-voltage factor reduction and increases significantly the sensitivity of the pixel to the ionising particles. A good trade-off between the dimensions of the PMOS transistor M_1 and the collection diode D_1 has been chosen in order to optimise the charge-to-current conversion gain and noise performances of the sensors.

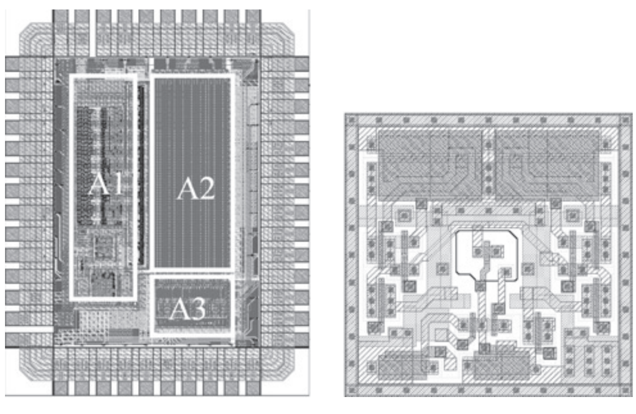

Fig. 2 *CMOS active sensor and layout of single pixel containing PhotoFET and readout circuit*

a CMOS active sensor
b Layout of single pixel

Measured results: The CMOS sensor presented in Fig. 2 is manufactured using a standard CMOS 0.35 µm technology (AMS: Austria Mikro System International AG) with high resistivity substrate [3]. An array of 16 × 64 pixels (Fig. 2*a* A2) with the PhotoFET proposed in Fig. 1 and the digital control bloc (Fig. 2*a* A1) are integrated. The signal output level delivered by the pixels is increased by using a current amplifier implemented in the chip shown in Fig. 2*a* A3. The layout of a single pixel is shown in Fig. 2*b*. The size of the pixel is 20×20 µm.

The results in Table 1 summarise the main measured characteristics of the CMOS active pixel sensor with the proposed PhotoFET. These measurements have been calibrated and performed with 5.9 keV X-ray photons delivered by an Fe^{55} source. Compared to a standard readout structure based on a source follower by NMOS transistors with the same power consumption from our previous work [4], a higher sensitivity and a better conversion gain with a large dynamic range and high readout speed have been obtained.

Table 1: Main measured characteristics of CMOS sensor using PhotoFET

Characteristics	Values
Main clock frequency	10 MHz
Charge-to-current conversion gain	105 nA/electron
Equivalent noise charges in input	29 electrons
Mean power consumption of one pixel	1.56 µW
Integrated current amplifier power consumption	1 mW
Readout time of PhotoFET	500 ns
Bandwidth of readout structure	65 MHz

Conclusions: A new design of PhotoFET using submicronic technology for monolithic active pixel sensors has been presented. The use of a PhotoFET in the current mode gives a high sensitivity and a better gain with large output dynamic range of several tens of microamperes available. Thus, the proposed PhotoFET is able to detect not only a single ionising particle but also a group of particles. With its high performance, this kind of sensor can be widely used for particle detection in high energy physics, biomedical imaging and space applications.

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